The Electrofluidic Brain: A Fluidic Network as an ancient Basement Layer for Neural Computation

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Abstract

This article offers a historical-philosophical reappraisal of brain function by revisiting the role of cerebral fluid dynamics in cognition. Tracing a lineage from early modern thinkers like Descartes—who invoked hydraulic metaphors and 'animal spirits'—to J.C. Bose's pioneering studies on electro-mechanical plant physiology, and culminating in contemporary findings on cerebrospinal fluid (CSF), extracellular space (ECS), and neurovascular coupling, we reveal a forgotten yet vital computational substrate. We argue that alongside the well-studied digital operations of neural circuits exists a slower, analog, evolutionarily older layer of electrofluidic computation. This system—comprised of ionic diffusion, convective CSF flow, and vascular modulation—not only supports but dynamically shapes neural activity. The brain emerges as an electromechanical ecology of electric pulses and fluid flows, where the mind is both a pattern of neural activity and a choreography of fluid flows.

Keywords: electrofluidic computation, cerebrospinal fluid (CSF), extracellular space (ECS), neurovascular coupling

1 Introduction

Our modern understanding of the brain has been dominated by the idea of circuits—networks of neurons connected by synapses, processing and transmitting signals

through sequences of electrical spikes. While this model has provided immense insights, it also risks narrowing our view to one specific form of computation. This paper explores an older, broader, and perhaps more foundational model of cognition — one grounded in the movement of fluids, ions, and mechanical oscillations.

Throughout history, thinkers have speculated about the role of bodily fluids in the generation of behavior and consciousness. In the pre-electrical era, hydraulic metaphors served as the dominant explanatory model for both motion and sensation. These ideas, often dismissed today as obsolete, may contain latent wisdom when reinterpreted through the lens of contemporary science. Early theories of 'animal spirits' flowing through hollow nerves might prefigure modern discoveries about extracellular diffusion and cerebrospinal circulation Manzoni (1998). The emerging picture in neuroscience reveals multiple fluidic systems that are not merely supportive but actively involved in information processing. The extracellular space (ECS) serves as a medium for volume transmission, allowing ions and neuromodulators to diffuse and shape neuronal communication Nicholson and Hrabětová (2017). The glymphatic system channels cerebrospinal fluid (CSF) through the brain in rhythmic cycles correlated with sleep and cardiac activity Aalling et al. (2015). Vascular networks dynamically regulate local blood flow in response to neural activity, forming bi-directionally coupled neurovascular circuits Kumar et al. (2021b,a); Gandrakota et al. (2010).

By bringing together historical perspectives, plant electrophysiology, and recent advances in brain science, we propose a unified theory: that the brain's fluidic systems represent a basement layer of neural computation. These networks are ancient, analog, and evolutionarily conserved. They mediate a logic of flow—what we call electrofluidic computation—underlying the more familiar logic of firing patterns and connectomes. This framework reframes the brain not as a static circuit board but as a living, breathing ecology of flows. It challenges the dichotomy between infrastructure and information, suggesting that what has long been considered physiological 'support' may in fact be the substrate of thought itself.

The structure of the paper is as follows: Section 1 introduces the historical lineage of fluid-based theories of mind, tracing the notion of 'animal spirits' and hydraulic analogies. Section 2 explores how early thinkers imagined the brain as a syncytial conduit for these flows. Section 3 turns to J.C. Bose's pioneering experiments, showing how electromechanical responses in plants reveal a proto-neural fluidic logic. Section 4 lists out several studies that point out evidences of electrofluidic signaling in plants. Section 5 delves into the role of the extracellular space (ECS) as a medium for neural computation, incorporating contemporary and historical research. Section 6 outlines the glymphatic system and cerebrospinal fluid (CSF) flows as integral to brain function. Section 7 expands the view to include vascular networks as fluidic computing systems. Section 8 presents examples of liquid computation in physical systems and draws parallels with brain fluidics. Section 9 proposes an evolutionary continuity from these ancient mechanisms to modern neural systems. Finally, Section 10 reframes the concept of mind, proposing that cognition emerges from the confluence of circuits and currents, and Section 11 concludes with

reflections on how this paradigm can reshape neuroscience.

Box 1: Defining electrofluidic computation

"Nature, in its earliest reasoning, computed not with silicon or synapse, but with sap and signal." —Inspired by J.C. Bose and Ramon y Cajal

Electrofluidic computation is a form of biological information processing in which electrical potentials, ionic gradients, and fluid flows interact within deformable, porous, and dynamic tissues to produce coordinated responses in living systems. Unlike traditional computation paradigms that rely on discrete logical operations (e.g., neurons firing or binary code), electrofluidic systems compute through continuous, field-like, and flow-based dynamics. In this paradigm, ionic gradients, osmotic forces, hydraulic pressures, and rhythmic pulses are not merely physiological side-effects—they participate directly in computation by shaping timing, intensity, and spatial patterns of signaling. Fig. 1 provides the definition for electrofluidic computation, and Table 1 provides a comparison between different computation paradigms.

The concept of electro-fluidic computation bridges ideas from J.C. Bose (1906–1928), who showed that plants propagate electrical signals through fluid-filled tissues to trigger hydraulic movements and adaptation, Thomas Willis and Rene Descartes – who envisioned the brain as a hydraulic network for sensation and motion (via "animal spirits"), and the modern glymphatic research – which reveals how sleep-driven CSF flow enables metabolite clearance and neural homeostasis through entrained pulsatile dynamics. This form of computation operates within soft-matter environments, such as extracellular spaces, vascular networks, and glial syncytia, where geometry, fluid viscosity, and membrane permeability dynamically influence signal propagation. The result is a hybrid system in which discrete electrical pulses are embedded within—and often entrained by—analog, field-like flow regimes. Electrofluidic computation underpins biological phenomena such as CSF flow entrained to sleep-related EEG oscillations, plant action potentials leading to ion-driven turgor changes, astrocytic swelling modulating extracellular signaling capacity, and vascular vasomotion influencing local neural gain. Unlike spike-based digital computation, this framework emphasizes ion fluxes and osmotic shifts, pulsatile cerebrospinal and vascular flows, and slow, analog field effects shaped by geometry, timing, and entrainment.

"To compute is to flow." — This paradigm aligns with early fluidic models of cognition, including the Belousov-Zhabotinsky chemical computers, liquid marbles, and even hydraulic integrators used to solve differential equations before digital electronics. This framing invites a shift from "brain as electrical circuit" to "brain as electrofluidic field," and opens avenues for modeling cognition in systems where flow, diffusion, and entrainment are primary. Moreover, the paradigm echoes ancient ideas—from hydraulic minds to plant sap logic—now measurable, modellable, and ripe for synthetic mimicry.

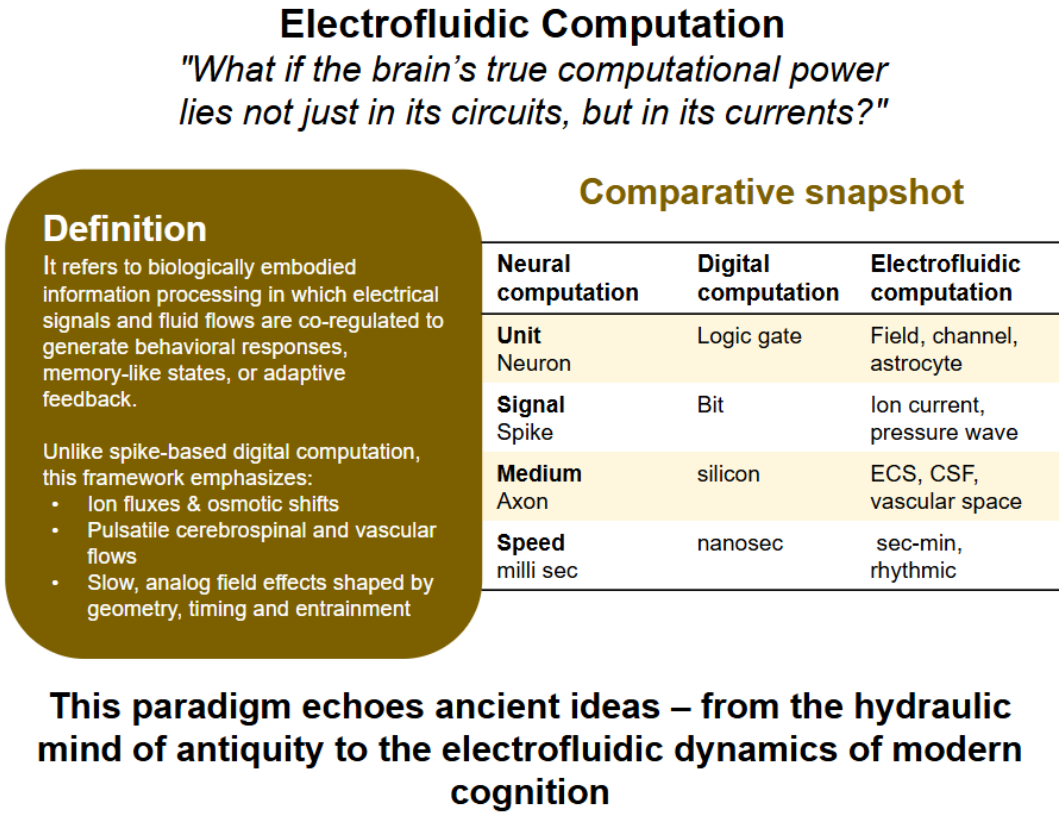
Electrofluidic Computation
"What if the brain's true computational power lies not just in its circuits, but in its currents?"
Definition
It refers to biologically embodied information processing in which electrical signals and fluid flows are co-regulated to generate behavioral responses, memory-like states, or adaptive feedback.
Unlike spike-based digital computation, this framework emphasizes:
• Ion fluxes & osmotic shifts
• Pulsatile cerebrospinal and vascular flows
• Slow, analog field effects shaped by geometry, timing and entrainment
Comparative snapshot
Neural computation
Digital computation
Electrofluidic computation
Unit Neuron
Logic gate
Field, channel, astrocyte
Signal Spike
Bit
Ion current, pressure wave
Medium Axon
silicon
ECS, CSF, vascular space
Speed milli sec
nanosec
sec-min, rhythmic
This paradigm echoes ancient ideas – from the hydraulic mind of antiquity to the electrofluidic dynamics of modern cognition

Figure 1: Defining electrofluidic computation and comparison between different computation paradigms

2 The Age of Hydraulic Minds: Descartes and the Animal Spirits

The idea that mental processes and bodily functions are driven by subtle internal fluids—often called "animal spirits"—has a long and complex history that predates the scientific revolution. The term "animal spirits" (spiritus animales) was inherited from ancient Greco-Roman medicine and philosophy. In Galenic physiology, for instance, animal spirits were believed to be a vital, airy substance produced in the brain, particularly in the ventricles, from a refinement of the blood. These spirits were thought to travel through hollow nerves to activate muscles and senses, forming the basis of perception, movement, and even imagination.

In this model, the nervous system was not a network of electrical wires but a series of pneumatic tubes. Physicians and philosophers from the medieval Islamic world—such as Avicenna (Ibn Sina)—expanded on Galenic models, describing complex systems of spirit movement that governed both physical and mental states. These traditions deeply influenced Renaissance thinkers and helped shape early modern theories of brain function.

One of the most influential figures to systematize this concept in the early modern

Table 1: Neural vs. Digital vs. Electrofluidic computation paradigms

Feature(s)	**Neural computation**	**Digital computation**	**Electrofluidic computation**
Signal type	Binary spikes (action potentials)	Binary data	Analog gradients, pressure waves, ion fluxes, fluid flows
Medium	Neuronal axons	Wires and silicon circuits	ECS, CSF, glia, vasculature, xylem/phloem
Processing style	Discrete-time, serial, symbolic	Discrete-time, serial, symbolic	Continuous-time, field-like, parallel
Temporal dynamics	Millisecond scale	Nanosecond scale	Seconds–minutes–hours (or slower rhythmic entrainment)
Connection type	Hebbian connections and plasticity	Hard-wired circuits	Reconfigurable flow networks
Energy efficiency	Active firing consumes (adenosine triphosphate) ATP	Movement of electrons requires energy	Low-energy entrained flow and osmotic regulation
Noise handling	Sensitive to fluctuations	High error-prone to noise	Averaged and robust via spatial summation
Examples	Cortical spike trains	CPUs (central processing unit)	Glymphatic flow, plant hydraulics, astrocyte–ECF (extracellular fluid) coupling

period was René Descartes (1596–1650). In his treatise De Homine (On Man) and later works such as Passions of the Soul, Descartes proposed that the pineal gland at the center of the brain acted as a valve or regulator of animal spirits. He believed that the spirits flowed from the brain's ventricles into the nerves, which he imagined as hollow tubes, reaching the muscles and causing them to inflate and contract.

To visualize this, Descartes drew analogies with the hydraulic statues and fountains of the French royal gardens, where hidden mechanisms used pressurized water to move arms, heads, or open gates in response to external triggers Brown (2023). In his model, external

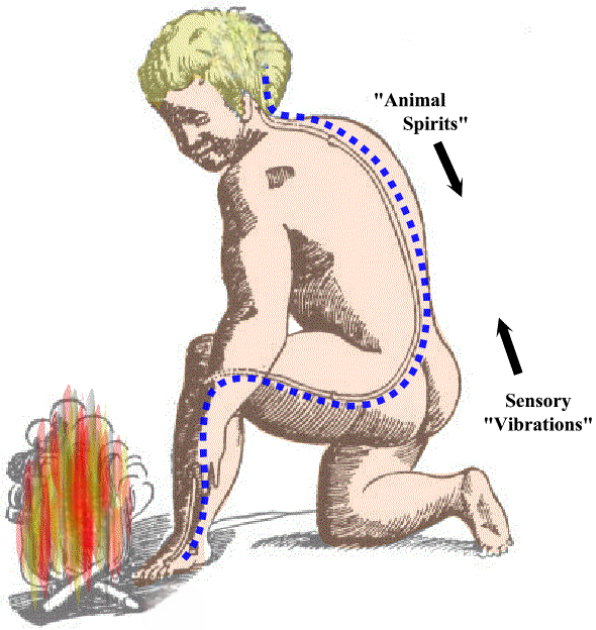

Figure 2: René Descartes' 17th-century (De Homine) illustration of reflex action, depicting the flow of 'animal spirits' from sensory input to the brain and then to motor output. (Public Domain)

stimuli (such as fire touching the foot) tugged on a "nerve filament," which opened a valve in the brain. This released a jet of animal spirits, which flowed through the nerves to inflate muscles, producing reflexive motion.

Descartes' theory was mechanical in spirit, but deeply physiological in consequence. He rejected Aristotelian vitalism and instead embraced the idea that human and animal bodies could be explained entirely in terms of fluid dynamics, pressure, and valves—what we might now call a kind of pre-biological engineering. Importantly, Descartes' model required that the brain operates as a kind of unified hydraulic architecture—a syncytium, or continuous tissue system—so that these spirits could flow freely through interconnected ventricles and channels. At the time, the neuron doctrine did not yet exist; the brain was a sponge-like mass with indistinct boundaries. The syncytial view was not unreasonable given the imaging tools of the time, and it served the logical consistency of fluid flow within a living system.

Other thinkers followed similar lines of reasoning. Thomas Willis (1621–1675), a contemporary of Descartes and a founder of modern neurology, believed that animal spirits were distributed through the "nervous juice" and circulated through the brain and spinal cord Eadie (2003). His work described the "Circle of Willis" and added anatomical detail to spirit-based theories of motion and cognition Martensen (1993).

In the 18th century, despite advances in microscopy and anatomy, the language of animal spirits remained embedded in medical and scientific literature. Some Enlightenment

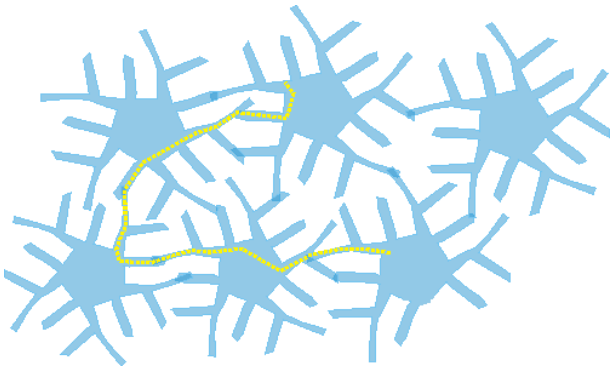

Figure 3: Schematic representation of a syncytium—an interconnected tissue network without clear cellular boundaries.

thinkers replaced "spirits" with more mechanical terms like "nervous fluid" or "ether," but the fundamental assumption of flow-based signal propagation remained Stahnisch (2012). Even in the early work of Luigi Galvani, who is credited with discovering bioelectricity, the concept of fluid pressure and vitality remained intertwined with emerging electrical models Piccolino (1997).

Thus, the idea that cognition, sensation, and movement arise from the flow of subtle substances through the nervous system persisted for centuries. It provided a framework for early neuroscience and reflected the technological metaphors of its era. Just as we now liken the brain to a computer, early moderns likened it to a hydraulic automaton.

Though eventually displaced by the neuron doctrine and electrophysiological models, the theory of animal spirits captures a deeper intuition: that motion and cognition are emergent properties of flow, not just of structure. As we will see, modern science is rediscovering the relevance of flow—this time in the form of cerebrospinal fluid, extracellular space, and glial dynamics—not as metaphor, but as measurable biological reality. This framework, far from being a naïve misunderstanding, must be understood in the context of the technological imagination of the time. In the pre-electrical era, hydraulics was the most advanced and effective model of mechanical power available. The 16th and 17th centuries saw a flourishing of hydraulic engineering, particularly in the design of elaborate water gardens and automata in Renaissance Italy and France. Examples include the Villa d'Este in Tivoli, with its gravity-fed fountains and musical water features Göker and Erdoğan (2020), and the Gardens of the Villa Lante, where water was choreographed to flow through stairs, sculptures, and grottoes Hu (2024). These systems were marvels of design, manipulating pressure, gradient, and flow to create responsive systems without electricity. For thinkers like Descartes, these gardens were not just sources of aesthetic pleasure, but models of nature. It is therefore understandable—indeed, reasonable—that he envisioned the brain as an exquisite hydraulic machine: a place where sensation triggered valves, and cognition directed jets of refined fluid through hidden pipes. What may appear as poetic or primitive in hindsight was, in context, a reflection of the most sophisticated technical paradigm available.

Moreover, the idea that the brain tissue formed a continuous syncytium—a network without discrete cellular boundaries—persisted well into the 19th century. A syncytium refers to a tissue in which cells are not completely separate but share cytoplasmic continuity, allowing substances to flow freely throughout the structure Golinowski et al. (1997). In such a model, the movement of fluids like animal spirits could occur seamlessly from the brain to the periphery and back. This assumption was crucial to the plausibility of hydraulic theories: without a continuous conduit, fluid flow would be interrupted, and the analogy to pressurized piping systems would collapse. Only by assuming a syncytial architecture could early thinkers maintain the idea of reflexive and motor function arising from fluid propulsion. Even as microscopy improved, many researchers continued to describe brain tissue in such terms, because no clear evidence yet existed for the neuron as a discrete functional unit. The later emergence of the neuron doctrine, championed by Ramón y Cajal in the late 19th century, finally displaced this view—but only after centuries of mechanistic reasoning built on the imaginative and engineering logic of flow—continuous and hollow—necessary for such fluid transmission. His ideas foreshadowed the later realization that the brain's function might involve system-wide flow, regulation, and responsiveness to pressure and fluid dynamics.

3 Bose and the Fluid-Electric Logic of Living Systems

Jagadish Chandra Bose (1858–1937) was a polymath whose contributions spanned physics, biology, and the philosophy of science. Working under the shadow of British colonial rule in India, Bose conducted pioneering research in environments that offered little institutional support and often open racial and cultural prejudice. Despite these constraints, he made groundbreaking discoveries that anticipated the future of multiple scientific domains. Notably, Bose was the first to experimentally demonstrate wireless electromagnetic transmission, even before Guglielmo Marconi. In 1895, he successfully transmitted signals across a distance using millimeter-length radio waves. While Marconi would go on to commercialize radio communication and receive widespread acclaim, Bose refused to patent his work, believing that knowledge should be freely shared. It wasn't until the 1990s that the IEEE formally recognized Bose's precedence in wireless signaling, correcting a long-standing historical oversight Sen (1997).

Following his early work in physics and radio waves, Bose turned his attention to the biological world Bose (1902). What followed was a monumental body of research into the electrical and mechanical behavior of plants. At a time when plant physiology was viewed primarily through the lens of passive growth and photosynthesis, Bose introduced a systems-level approach that treated plants as complex, responsive, and signaling organisms Bose (1907); Bose and Guha (1922). He designed exquisitely sensitive instruments to measure electrical responses in plant tissues, revealing that they react to stimuli much like animal nerves do Bose (1906).

Bose showed that plants exhibit action potential-like signals, measurable and reproducible, which travel through specialized internal channels (as'ayas) Bose (1906,

1907). These signals trigger physiological changes such as the folding of Mimosa pudica leaves or the snapping of the Venus flytrap. Importantly, these responses did not rely on neurons or muscles but on turgor pressure shifts and ion fluxes. His work thus demonstrated a coupled system of electrical and fluidic signaling in plants—what we now recognize as a form of non-neuronal cognition.

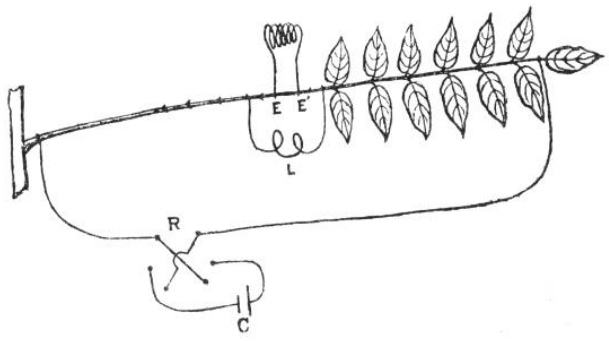

Figure 4: A schematic of the experimental setup used by Bose to demonstrate how electrical stimulation causes motor response in the leaves of mimosa pudica Bose (1919) (Public Domain)

In taking this approach, Bose was far ahead of his time. He did not isolate biological mechanisms into separate silos but saw them as parts of a continuous, integrated system. This was not merely plant electrophysiology—it was plant neurobiology before its time. His insights challenge anthropocentric models of intelligence and open the door to understanding cognition as a generalized property of organized matter, rather than something exclusive to animals with brains Bose (1906, 1927).

Bose's seminal work forces us to rethink what it means to signal, to compute, and to respond. One of his most remarkable contributions was the detailed elucidation of motor response in plants—particularly how electrical and fluidic events coincide to produce coordinated motion Bose (1908). Bose demonstrated that when a plant like Mimosa pudica is touched, a measurable electrical impulse is generated at the point of contact Bose and Das (1925); Bose and Chandra (1916); Bose (1914). This impulse then travels through the plant's internal channels, initiating a cascade of physiological changes. Chief among these is the redistribution of fluids within the pulvini, the motor organs at the base of the leaflets. As ions move across cell membranes, water follows osmotically, leading to turgor changes in specific cells. The result is a rapid loss or gain of stiffness and volume in targeted regions, which causes the leaf to fold or droop in a coordinated response Bose et al. (1926). Importantly, Bose showed that the electrical impulse, fluid redistribution, and mechanical movement were not isolated events but tightly coupled components of a single signaling process Bose (1925, 1913). This was a true electromechanical loop in a living organism without nerves or muscles—a profound insight into the deep logic of life's responsiveness.

Another dimension of Bose's fluid-electric understanding came through his investigations into the ascent of sap—the mechanism by which water and nutrients travel

upward through a plant's vascular system Bose (1923); Bose et al. (1924). At the time, the prevailing explanation relied heavily on the capillary effect, transpiration pull, and cohesion-tension theory, suggesting that water moved passively upward due to evaporation at the leaf surfaces and the cohesive properties of water molecules. Bose, however, offered an active physiological model: he proposed that cells at the root and stem junctions functioned like micropumps, generating rhythmic electrical oscillations that helped propel water upward. He even recorded pulsations in plant tissues that coincided with sap movement, implying the presence of a bioelectric rhythm underlying the process Bose et al. (1928). This view echoed his findings in leaf movement, where an electrical impulse triggers fluid redistribution and mechanical response Bose (1929). In both cases—whether folding a leaf or raising water through the stem—Bose identified a coupled mechanism: bioelectric signaling sets off changes in fluid pressure, which in turn produces a macroscale outcome, be it motion or transport. In this way, the motor function and sap ascent shared a common electromechanical logic, challenging the separation between active signaling and passive support in plant physiology Bose (1923); Bose et al. (1928).

Bose's legacy invites a deeper appreciation for plant intelligence, not in metaphorical terms but in mechanistic ones. His work blurs the boundary between nervous and non-nervous systems, between computation and circulation. In the fluid-electric reactions of plant tissues, we glimpse the remnants of an ancient computational logic—one that may persist, in evolved form, within the layered architecture of the human brain itself.

In the fluid-electric reactions of plant tissues, we glimpse the remnants of an ancient computational logic—one that may persist, in evolved form, within the layered architecture of the human brain itself. Electrophysiological studies of plants revealed that even without neurons, organisms could perceive, compute, and act. In Mimosa pudica, for instance, mechanical stimuli generate electrical signals that travel through fluid-filled tissues (as'ayas), culminating in turgor-based movement Bose (1906). Bose's experiments showed that bioelectric and fluidic mechanisms are intertwined. Plants, devoid of nerves, display a primitive form of electromechanical cognition—a decentralized but effective signaling architecture. This discovery hints at a time when life coordinated behavior through coupled fluid-electric pathways, long before specialized neurons evolved.

4 Electrofluidic Signaling in Plants: Evidence for a Plant 'Brain'

The idea that plants possess electrofluidic systems functioning akin to a 'brain' has long been explored. Electrical signals in plants are known to propagate through vascular channels such as the phloem, xylem, and cambium, reaching all parts of the plant body Baluška and Mancuso (2009); Baluška et al. (2009); Baluška (2010); Trebacz et al. (2006); Volkov (2012); Huber and Bauerle (2016); Souza et al. (2017); de Toledo et al. (2019); Segundo-Ortin and Calvo (2022). Recent studies have shown that long-distance transmission of electrical signals from sensor to effector sites is primarily facilitated by the

phloem Hedrich et al. (2016); Volkov (2012); Volkov et al. (2019). This reinforces the notion that the vascular system plays a central role in inter-organ and systemic communication Yoo et al. (2013); Calvo and Lawrence (2022). Importantly, the molecular mechanisms underlying such electrical transmission—such as ion channel activity—are evolutionarily older than the nervous systems of animals Baluška and Levin (2016). Like neurons, plant cells also generate electrical responses to various stimuli, including action potentials (APs) Baluška (2010); Baluška and Levin (2016); Baluška and Mancuso (2018, 2020); Felle and Zimmermann (2007). These APs travel through sieve tubes and parenchyma cells located in the protoxylem and phloem, respectively Samejima and Sibaoka (1983); Fromm and Eschrich (1988). Non-damaging stimuli, such as touch, can evoke APs that propagate through the plant and activate movements, for instance, at the tertiary pulvini of leaves. The propagation speed of APs ranges from approximately 3–7 mm/s in the rachilla and 6–44 mm/s in the petiole Sibaoka (1966). In contrast, damaging stimuli can elicit both APs and variation potentials (VPs), also known as slow wave potentials Houwink (1935), which travel more slowly—typically at 1–4 mm/s in the petiole. A third type of electrical signal observed in plants is the system potential (SP), which is evoked by external factors and involves a hyperpolarization event mediated by the activation of H+-ATPases in the plasma membrane Zimmermann et al. (2009).

Through plasmodesmata, plants utilize both chemical and electrical synapse-like mechanisms Calvo and Lawrence (2022); Volkov and Beilby (2017), functionally similar to animal gap junctions. Rapid intercellular communication via vesicle trafficking—facilitated by adhesion domains—has been compared to neuronal synapses Baluška et al. (2004). Remarkably, extracellular application of the hormone auxin can evoke electrical responses. Furthermore, plants use classical neurotransmitters such as GABA, acetylcholine, dopamine, serotonin, glutamate, histamine, and noradrenaline for signaling Volkov and Beilby (2017); Volkov and Shtessel (2020); Kulich et al. (2015). For example, glutamate application depolarizes cells in the root-stem transition zone Baluška (2010). This zone also integrates sensory-motor signaling via auxin transport and vesicle recycling, facilitating processes like cell elongation and root tropisms that allow the plant to adapt to its environment Baluška et al. (2009). Uniquely, this region also exhibits synchronized electrical activity Masi et al. (2009), suggesting it plays a decision-making role by coordinating phenotypic responses from root to shoot. Mechanical injury can alter xylem hydraulic pressure, initiating systemic depolarization waves throughout the plant—a phenomenon termed the hydraulic hypothesis Stanković and Davies (1998). Wounding also triggers systemic defense gene expression via glutamate receptor-like (GLR)-mediated membrane depolarizations Nguyen et al. (2018); Pantazopoulou et al. (2023). In Arabidopsis, wound signals propagate between leaves through vascular elements, specifically phloem sieve elements and xylem contact cells. Larval feeding by Spodoptera littoralis on Arabidopsis thaliana generates electrical signals at the wound site, which then spread to adjacent leaves Mousavi et al. (2013). This rapid electrical signaling is coupled with hydraulic changes in the xylem and phloem via an electro-osmotic mechanism Farmer et al. (2020).

Collectively, these findings demonstrate that plants, like animals, possess complex

electrofluidic systems that enable them to perform a wide range of physiological and behavioral tasks. Beyond these examples, plant electrical signals are also capable of encoding more sophisticated information. For instance, Chiolerio et al. (2025) demonstrated that spruce trees (Picea abies) exhibit synchronized bioelectrical activity and changes in entropy—referred to as the electrome—in anticipation of environmental events such as a partial solar eclipse, hours before it occurred.

5 The Cerebral Extracellular Space – A Fluid Medium for Computation

The previous sections have shown how biofluids, when modulated by electrical signals, can induce mechanical responses in tissues—forming the basis of motor activity and fluid transport. But how do these fluid flows propagate within the dense and geometrically intricate microenvironment of the brain? The answer lies in the extracellular space (ECS)—the complex network of microscopic corridors that thread between cells. As the primary medium through which ions, neurochemicals, and even cerebrospinal fluid navigate, the ECS emerges as a critical microanatomical infrastructure for electrofluidic signaling. In this section, we explore the ECS not simply as passive interstitial fluid, but as a structured and responsive computational medium that forms the foundational terrain of the electrofluidic brain.

Across multiple foundational works—including Syková and Nicholson (2008); Nicholson (1980); Syková et al. (1996); Bach-y Rita (1993); Agnati et al. (2000, 2005) —a consistent picture emerges: the brain's extracellular space (ECS) is not a passive milieu but a dynamic and responsive fluidic substrate for information processing. These studies collectively assert that intercellular communication in the CNS occurs not only through direct synaptic connections ("wiring transmission") but also through diffusion-based processes, termed volume transmission. Volume transmission refers to the dissemination of signaling molecules—such as neurotransmitters, ions, peptides, and even gases—through the ECS to act on multiple target sites, sometimes far from the point of origin. This mode of communication contrasts with the traditional neuron doctrine's emphasis on localized, point-to-point signal transfer via synapses. According to Agnati and colleagues Agnati and Fuxe (2014); Marcoli et al. (2015), volume transmission complements wiring transmission, expanding the brain's capacity for coordination, modulation, and distributed computation. In his extensive review, Nicholson (1980) elaborates on the ECS as a tortuous, geometrically complex environment whose characteristics significantly impact the spread of ions and molecules. He identifies key parameters such as volume fraction and tortuosity—terms later popularized by Syková—as central to understanding how signaling occurs within this space Syková et al. (1996). These physical constraints shape the delay, strength, and spatial reach of chemical signals. Syková and Nicholson (2008) builds on this by measuring changes in ECS under different physiological and pathological states.

Since the ECS is an electrolytic medium, and since neuronal firing activity depends on

ionic fluxes crossing the neural membrane, neural computation is deeply dependent on the ECS layer. For instance, the influx of calcium ions (Ca^{2+}) into the presynaptic terminal is essential for vesicle fusion and neurotransmitter release. If a presynaptic terminal has recently transmitted, it can cause a local depletion of Ca^{2+} in the ECS, temporarily impairing the ability of adjacent terminals to fire. Similarly, when a neuron is active, potassium ions (K^+) flow out of the cell during repolarization. This leads to elevated extracellular K^+ concentrations, which can excite neighboring neurons by depolarizing their resting membrane potentials. These examples show that neurons do not operate in isolation; they are coupled through shared ionic environments, allowing for extrasynaptic communication mediated by the ECS. One particularly striking observation she makes is that electrical activation of neural tissue results in astrocyte swelling. This occurs due to localized ionic shifts, which draw water osmotically into astrocytes, thereby altering the local ECS volume. This process—where electrical events lead to fluid redistribution and cellular swelling—mirrors the kind of electromechanical response observed by Bose in plant tissues. Just as Bose demonstrated that an electrical signal in Mimosa pudica initiates ion fluxes followed by water movement and turgor changes, Syková and Nicholson (2008) shows that neural excitation can lead to water influx into glial cells and consequent ECS shrinkage. In both systems, electricity and fluid dynamics are coupled to produce physiological responses that modulate the information-processing environment.

Bach-y Rita (1993) framed the ECS as a genuine neurotransmission medium, proposing that diffusion through extracellular fluid is a valid and central mode of communication in the brain. He likened this to a chemical field that overlays the anatomical circuitry, enabling slow, sustained, and integrative signaling that cannot be captured by electrophysiology alone. This notion redefines the ECS as an informational field, operating in parallel to fast electrical signaling, and essential for mood regulation, sensory integration, and neuroplasticity.

All of these works converge on a key insight: the ECS is a morphodynamic space—its structure changes in response to use, stress, metabolic demand, and time of day. It allows the brain to compute in analog, using field-like propagation, graded responses, and spatial averaging. This creates a fluid-based logic, where information is shaped not by discrete pulses, but by concentrations, gradients, and geometry. In this view, cognition emerges not solely from spike trains or synaptic weights but from the dynamic behavior of extracellular fluids, glial modulation, and their influence on neural excitability. The ECS serves as a deep, continuous layer of computation—one that supports and stabilizes the faster, symbolic operations of the neural network.

Taken together, the literature recasts the ECS as a computational scaffold—slow, analog, and state-sensitive. It operates as a liquid logic field, resonating with early intuitions of flow-based brain function and aligning precisely with this paper's overarching thesis: that the brain's intelligence is embedded not just in neurons, but in the geometry of fluid.

6 The Return of Flow: CSF and the Glymphatic Renaissance

Cerebrospinal fluid (CSF) is a clear, colorless fluid that bathes the brain and spinal cord, providing both physical cushioning and a chemical environment essential for homeostasis. It is produced primarily by the choroid plexus in the brain's ventricles and flows through a well-defined pathway: from the lateral ventricles to the third and fourth ventricles, into the subarachnoid space, and around the brain and spinal cord. Eventually, it is absorbed into the venous system via arachnoid granulations. In total, the CSF is turned over several times a day, ensuring the regular clearance of metabolic waste, distribution of neuroactive substances, and regulation of intracranial pressure. For decades, CSF was thought to be a protective and homeostatic fluid, however, recent works have challenged this simplistic view. With the identification of the glymphatic system, that is a glial-dependent clearance pathway have shown the prominent role of CSF in the physiological housekeeping of the brain. Nedergaard and colleagues Nedergaard (2013) proposed that the glymphatic system comprises of the directed flow of CSF along perivascular spaces, facilitated by aquaporin-4 channels located in astrocyte endfeet. This CSF then exchanges with interstitial fluid, to sweep off waste products (such as beta-amyloid and tau) that are caught up in neurodegenerative diseases Xie et al. (2013).

Glymphatic circulation is not a passive process and it is dynamically regulated by neural and physiological rhythms. Studies have revealed that the process of glymphatic clearance is markedly increased during slow-wave sleep, during which the interstitial space expands by nearly 60% to allow enhanced convective flow van Hattem et al. (2025). Furthermore, cardiac pulsations and respiratory oscillations work like mechanical drivers facilitating rhythmic propulsion through perivascular network of the brain Hamill (2023). Therefore, the glymphatic system illustrates a neural-fluidic coupling, in which brain's electrical and vascular rhythms entrain different processes such as fluidic movement, embedding computation and metabolism within a unified oscillatory regime.

Fultz et al. (2019) in their recent work confirms this entrainment by showing CSF flow's direct coupling with neural activity and hemodynamics. With the help of simultaneous EEG (electroencephalogram) and fMRI (Functional magnetic resonance imaging) recordings, they demonstrated that large waves of CSF inflow into the brain's ventricles were tightly synchronized with low-frequency neural oscillations and hemodynamic changes, especially during non-REM sleep. These observations suggest that CSF dynamics are orchestrated brain-wide by a complex interplay of electrophysiological and vascular events. This reinforces the idea that fluidic movement in the brain is not just a supportive but an integrative element in neural computation and systemic regulations.

Such a recently recognized function of CSF flow reshapes our understanding of the brain's infrastructure. Instead of merely serving as a passive coolant, the pulsatile dynamics of CSF represent a primitive yet integral computational rhythm, working in tandem with neuronal activities to support various functions such as memory, repair, and

overall cognitive integrity. In the context of this paper, the glymphatic system forms a bridge between electrophysiology and fluid dynamics, echoing Bose's insights into electromechanical life and extending Syková's vision of the extracellular environment as a substrate for computation.

6.1 Bridging Plant Electrofluidics and Glymphatic Dynamics

While the glymphatic system has been recently characterized in neuroscientific literature as a glial-regulated clearance mechanism, its functional architecture and rhythmicity exhibit striking parallels with plant electrohydraulic physiology. This resemblance opens the door to a broader conceptual framework, in which glymphatic circulation is understood not merely as a byproduct of vascular dynamics, but as an evolutionarily conserved mode of analog fluidic signaling. In plants, long-distance transport of water and solutes occurs through xylem conduits, modulated by aquaporins, turgor pressures, and rhythmic pulses Chaumont and Tyerman (2014). Similarly, in the brain, Aquaporin-4 (AQP4) channels located on astrocytic endfeet lining perivascular spaces facilitate convective influx of cerebrospinal fluid (CSF) into the brain parenchyma Liu et al. (2017); Szczygielski et al. (2021). This influx is most active during slow-wave sleep, when the interstitial space expands and permits efficient exchange between CSF and interstitial fluid (ISF), thereby supporting glymphatic clearance of neurotoxic solutes such as β-amyloid and tau Corbali and Levey (2025). This astroglial-driven, aquaporin-gated mechanism resembles xylem loading and unloading in root and leaf tissues, which similarly rely on rhythmic aquaporin regulation and ion-mediated osmotic gradients. Moreover, just as plant sap ascent is now known to involve bioelectric modulations and pulsed fluidic motion (as demonstrated by Bose), CSF movement is entrained to systemic physiological oscillations such as cardiac pulsations, respiration, and the sleep-wake cycle. Furthermore, the brain's waste efflux via perivenous outflow and meningeal lymphatics may be viewed as the central nervous system's analog to toxin extrusion mechanisms in root endodermal cells, which dynamically regulate osmotic pressure, signaling molecules, and detoxification. These structural and functional analogies suggest a deep homology in how multicellular systems evolved rhythmic, glia-like tissues to regulate flow-based computation and maintenance—a hypothesis that we believe warrants experimental exploration. Table 2 tabulates parallels between fluidic systems of plants and brains

Table 2: Conceptual parallels between plant and brain fluidic systems

Plant System	**Brain System (Glymphatic)**
Xylem (sap flow) driven by root pressure, circadian rhythms, and aquaporins	Periarterial CSF inflow driven by cardio-respiratory impulses, cerebral arterial pulsatility, and AQP-4 complex integrity
Bioelectric pulses modulating turgor and flow (Bose)	EEG-linked slow oscillations driving CSF pulsatility and interstitial exchange
Toxin efflux via endodermal membranes, root exudates	Interstitial solute clearance via perivenous glymphatic outflow
Hydraulic signal transduction (e.g., in *Mimosa pudica* or Venus flytrap)	Neurovascular-glial entrainment of CSF, ECS, and neural activity
Aquaporin-regulated water redistribution	AQP4-regulated convective CSF-ISF coupling

7 Vascular Computation – Yet Another Biofluidic Computing Network

The article builds the case that an ancient electrofluidic network was the precursor to the nervous system. Initially, this network in plants functioned both as a nutrient channel and a slow communication system. In animals, it later differentiated into two specialized systems: the nervous system, which enabled rapid communication, and a fluidic system associated with cerebrospinal fluid (CSF) flow. This section extends the argument by proposing that the vascular system is another specialized fluidic network, operating alongside CSF flows.

Structural similarities between the nervous and cardiovascular systems were noted as early as 1543 by Andreas Vesalius Barr (2015). Vasomotion—the oscillatory change in arteriolar diameter—modulates vascular resistance in various physiological and pathological states such as pregnancy, pre-eclampsia, and hypertension Funk et al. (1983); Meyer et al. (1993, 2002); Gratton et al. (1998). Oscillatory flow in capillary beds, driven by vasomotion, may improve tissue oxygenation compared to steady blood flow Nilsson and Aalkjær (2003). Vasomotion demonstrates a wide array of temporal and spatial rhythms, ranging from regular to chaotic patterns Griffith and Edwards (1994). Experiments have shown that vasomotion induced by agents like histamine can either provoke or suppress oscillations in rabbit ear arteries Griffith and Edwards (1995), and exhibit nonlinear dynamics such as quasiperiodicity and type-III intermittency De Brouwer et al. (1998); Naka et al. (2003). Studies in rats reveal nephron–nephron coupling and the spread of vasomotion in both hypertensive and normotensive conditions Kallskog and Marsh (1990); Yip et al. (1992); Chen et al. (1995); Wagner et al. (1997); Marsh et al. (2007). Theoretical models show that irregular (chaotic) vasomotion in skeletal muscle can enhance tissue

oxygenation more effectively than regular oscillations Pradhan and Chakravarthy (2007); Pradhan et al. (2007); Pradhan and Chakravarthy (2009, 2011). Collectively, these findings underline that vasomotion is a spatio-temporal phenomenon arising from dynamic interactions among vessel segments to optimize microcirculatory function.

The hemo-neural hypothesis, proposed by Christopher Moore and Rui Cao Moore and Cao (2008), posits that vascular flow can play a computational role. They argue that blood flow can actively modulate neural function, suggesting that vascular dynamics are embedded within the brain's computational processes. This shifts the view of neurovascular coupling from a one-way delivery service to a dynamic, bidirectional system. Glial cells, especially astrocytes, are central to neuronal energy supply; they regulate glucose uptake in response to synaptic activity Tsacopoulos and Magistretti (1996). The density of glial cells reflects local neural metabolic demand Sherwood et al. (2006). Glial networks relay metabolic signals from neurons to microvessels and manage nutrient delivery from blood vessels to neurons Charles (2005); Magistretti (2006). Rather than serving solely as passive support, glia function as both signaling intermediaries and distributors of metabolic resources. The astrocyte-neuron lactate shuttle theory Pellerin et al. (1998), supported by experimental data Kasischke et al. (2004), describes how astrocytes convert vascular glucose to lactate, supplying neurons with the necessary energy for synaptic transmission.

Work by Gandrakota et al. (2010) shows that glial cells help regulate perfusion, smoothing hemodynamic fluctuations and ensuring steady nutrient supply—akin to homeostatic buffering in computing. Stable neural responses depend on precise coordination of metabolic demand and supply via the glial-vascular interface, resembling associative network dynamics Hinton et al. (2006). Astrocytes in the visual cortex display "tuned responses" to stimuli, further highlighting their role in information processing Schummers et al. (2008). Subsequent modeling studies Kumar et al. (2021b,a) introduced bidirectionally coupled, self-organizing neurovascular networks capable of reproducing orientation-selective cortical responses observed in neuroimaging. Their findings suggest neural and vascular networks co-evolve, shaping each other's structure and function for optimal efficiency and adaptability. This cooperative interaction is crucial for maintaining stable yet flexible cortical maps, a foundation for higher cognition. Further research Kumar et al. (2022) demonstrated that neural architecture and activity patterns directly influence vascular growth, emphasizing the reciprocal relationship between neural and vascular systems.

In sum, these studies reinforce the concept of the vascular network as a "co-processor"—not just a supplier, but also a participant in computation, regulation, and adaptation. Thus, vascular computation aligns with the extracellular space and glymphatic systems as a key component of the electrofluidic brain, constituting an intricate lattice of flows, fields, and feedbacks underpinning cognition.

8 Liquid Logic: Toward an Electrofluidic Theory of the Brain

According to the view developed in this article, the brain is not merely a neural network supported by fluids, but a computational fluidics engine, whose logics are as much about circulation and chemistry as they are about voltage and spike timing. To better appreciate how such computation can occur in fluidic systems, Adamatzky's work offers a taxonomy of liquid computers—physical substrates that use flowing media to carry out logic operations Adamatzky (2019). These include reaction-diffusion processors, where chemical patterns such as the Belousov-Zhabotinsky reaction implement logic gates via wavefront interactions Adamatzky and De Lacy Costello (2017); Adamatzky (2004). Similarly, droplet-based processors use the controlled motion, collision, and splitting of microdroplets in oil or aqueous media to represent and transform data Katsikis et al. (2015); Asghari et al. (2020); Zhang et al. (2011). Another example is liquid marbles, hydrophobic-coated droplets that roll over surfaces and interact mechanically or chemically, effectively serving as mobile logic units Sun et al. (2022); Tong et al. (2025); Cheow et al. (2007). Vortex-based computation is also notable—where the dynamics of rotating fluid flows in confined geometries can embody rules of logic, memory storage, and timing Christianto and Smarandache (2022); Strasser (2022); Jung et al. (2012). These systems often exploit nonlinear properties of fluids—thresholds, oscillations, phase transitions—to simulate computational primitives such as logic gates, delay lines, and integrators. What is striking is that many of these principles resonate with processes observed in the brain: waves of potassium spreading through ECS, convective pulses of CSF, or vascular oscillations entrained by neural activity. Such analogies are not merely poetic; they invite the serious proposition that the brain's fluidic systems may operate in accordance with similar principles, evolved and specialized for living computation.

Thus, the electrofluidic theory suggests that beneath the digital-like neural firing patterns lies a substrate of analog, soft-matter computation, sculpted by evolution to harness the power of flows, fields, and emergent material properties. One of the earliest and most compelling examples of fluid-based computation is the use of hydraulic algebraic machines, which employ networks of fluid channels, valves, and chambers to simulate the behavior of algebraic equations. In such systems, pressure differentials and fluid heights represent mathematical variables, allowing for real-time, analog solutions to complex problems. These devices were capable of modeling polynomials and differential equations with surprising accuracy, long before digital computers emerged.

Closely related are hydraulic integrators, developed in the early 20th century to solve differential equations that arose in engineering and physics. These analog computers used the continuous flow of fluid through carefully calibrated resistances and capacitances—hydraulic analogs to electrical components—to perform integration over time. These machines highlight the deep structural analogy between electrical and hydraulic domains, reinforcing the plausibility of a fluidic basis for dynamic computation in biological systems. Another captivating category is that of fluid mappers and maze solvers.

These setups often consist of fluid-filled mazes or branching networks where dye or tracer particles find optimal pathways, effectively "solving" problems like shortest paths or flow minimization Fuerstman et al. (2003); Zhang and Li (2023); Suzuno et al. (2014). Such systems offer a physical and intuitive model for computation through spatial geometry and constraint satisfaction—a metaphor that may resonate with how fluids navigate through the tortuous architecture of the brain's vasculature and ECS. Intrathecal tracer study by Ringstad et al. (2017) using gadolinium in humans for visualizing glymphatic flow across brain topology to assess metabolic function is an example of modern versions of hydraulic maze solvers.

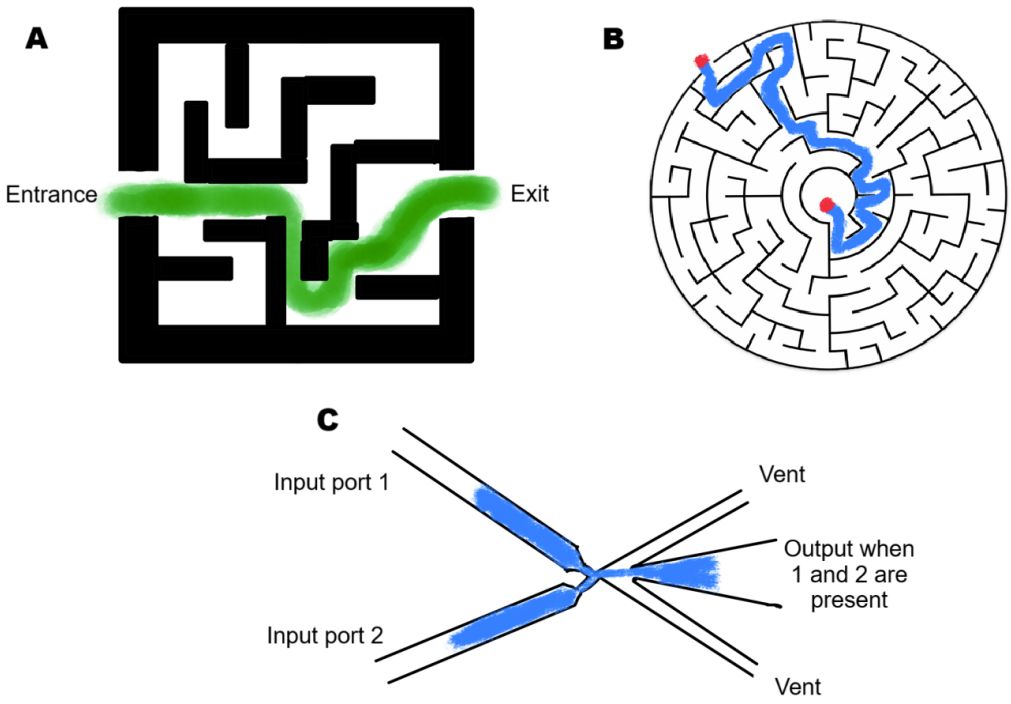

Figure 5: Illustrations of different liquid computational tasks. A,B- liquid solving different maze problems. C- schematic representation of fluidic NOT-AND gate.

Further innovations include droplet tracing fluid mappers, where the behavior of microdroplets on patterned surfaces encodes logical decisions. As droplets merge, repel, or follow specific paths dictated by surface tension and chemical gradients, they enact computational operations without the need for electronics. These systems reveal how even simple fluidic elements can be harnessed for logic, storage, and signal propagation. Lastly, the field of fluidic logic formalizes these phenomena into structured circuits, with fluid-based equivalents of AND, OR, and NOT gates. Often used in environments hostile to electronics—such as inside the human body or outer space—fluidic logic circuits provide robust, miniaturized alternatives for control and computation. The behavior of these systems illustrates that logical operations can emerge from pressure thresholds, turbulence, and nonlinear flow interactions, offering a powerful analogy for the complex dynamics of neural-fluidic interactions in the brain. Fig. 5 shows illustrative examples of liquid

computational tasks.

8.1 From Fluidic Biology to Biohybrid Computation

The conceptual and structural analogies between plant electrohydraulic signaling and brain glymphatic flow do more than enrich our understanding of evolution—they also offer a novel blueprint for biohybrid computing. Traditional neuromorphic computing systems model spike trains and connectivity matrices, but they overlook the role of flows, diffusion gradients, and analog field effects—elements that are increasingly recognized as integral to biological computation. Plant systems demonstrate that distributed intelligence can emerge without neurons, through the orchestration of electrical impulses, hydraulic oscillations, and chemical signaling. These mechanisms exhibit many of the desirable features of a computing substrate: low-energy information propagation, inherent robustness to noise, spatial parallelism, and adaptability to environmental stimuli. Likewise, the glymphatic system, though primarily studied in metabolic and homeostatic terms, operates as a spatiotemporally modulated fluidic network, whose behavior is shaped by oscillations in sleep, heart rate, respiration, and neural activity. These entrained flows represent a form of fluidic memory and state-dependent gating—core attributes of analog computation.

We propose that biohybrid fluidic computing systems can draw from both these biological precedents. Key possibilities include: a) aquaporin-mimetic membranes that act as flow-gated transistors for ionic or molecular computing. b) electrofluidic actuators that simulate plant pulvinar mechanics or astrocytic swelling to regulate signal throughput. c) oscillatory hydrogel logic circuits that mimic circadian-entrained sap movement or CSF pulsatility. d) non-neuronal field computing models where computation arises through the modulation of fluid geometry, concentration fields, and rheological properties—akin to how ECS tortuosity or phloem ion dynamics shape signaling. Such fluidic logic architectures could enable computing systems that operate on material flows rather than binary codes, supporting a class of devices that are soft, adaptive, and embedded—perhaps even capable of co-evolution with their environment.

9 Evolutionary Continuity: From Primitive Currents to Neural Codes

If we step back and examine the patterns uncovered across plant electrophysiology, glymphatic dynamics, extracellular signaling, and vascular computation, a larger picture begins to emerge—one of deep evolutionary continuity in the mechanisms of biological information processing. The evolution of nervous systems did not begin ex nihilo with the appearance of the neuron, but rather grew from a substrate of electrofluidic coordination mechanisms—primitive, yet computationally potent. In organisms such as plants, where classical neurons are absent, J.C. Bose demonstrated that electrical signaling and fluidic shifts can lead to motor responses and coordinated behavior. This suggests that electromechanical and fluid-based signaling systems were precursors to modern nervous

systems. The presence of action potentials, hydraulic flows, and distributed networks of responsive tissue in these simpler organisms underscores an ancient form of proto-cognition.

This idea is echoed in recent neuroscience findings that emphasize the computational roles of non-neuronal systems: glia regulate information transfer, CSF oscillations correlate with memory consolidation, and vascular networks adaptively respond to neural demand. These examples point to a layered architecture of the brain, where a more ancient, slower, analog form of computation coexists with the faster, digital computations of neurons.

We may thus posit that neural circuits are evolutionary overlays atop an older fabric of rhythmic flows and chemical gradients—a fabric still active today, though often overlooked. Much like the evolutionary story of lungs emerging from swim bladders or feathers from reptilian scales, the modern neuron may be seen as an evolved specialization of pre-existing electrofluidic architectures. This continuity challenges the reduction of cognition to spike trains and connectomes alone. It encourages us to reinterpret cognition as emerging from the interplay of structure, flow, and field—a dynamic, embodied process embedded in the very material properties of life.

10 Reframing Mind: From Circuits to Flows

With the accumulated evidence for fluid-based signaling systems—ranging from CSF pulsations and extracellular chemical gradients to vascular-neural interactions and plant electrophysiology—it becomes necessary to reframe our conception of mind itself. Traditional cognitive neuroscience has relied heavily on the metaphor of the brain as a circuit, where synaptic connections and electrical impulses encode, transmit, and process information. However, the emerging picture suggests that flow, diffusion, and oscillation are equally fundamental to how information is managed in living systems.

Rather than viewing neural networks as discrete nodes wired together like an electrical circuit board, we might envision them as embedded in a liquid landscape—where the timing, amplitude, and persistence of signals are modulated by dynamic fluidic contexts. In such a paradigm, the ECS, CSF, and vascular flows act not as passive backdrops but as active participants in the regulation of neural activity, influencing computation in a spatially distributed and temporally fluid manner.

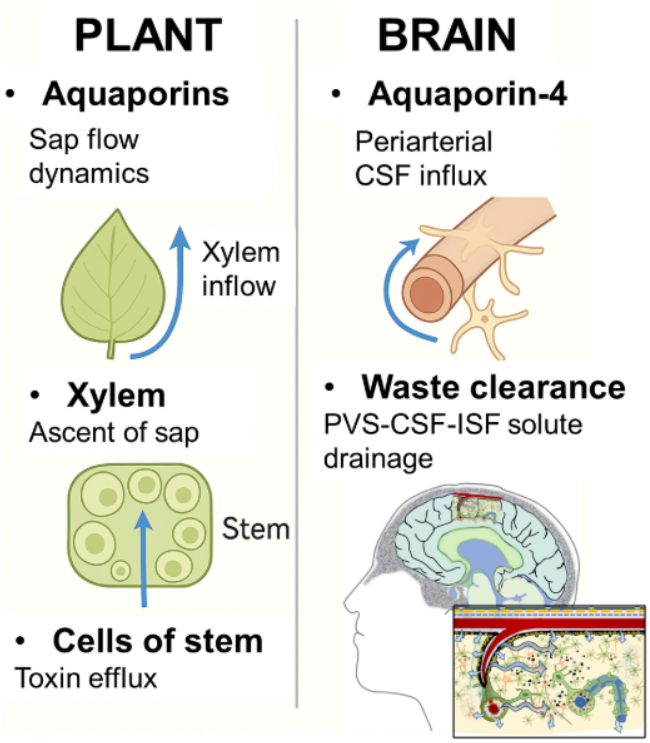

Figure 6: A summary diagram linking plant electro-fluidic features to brain fluidic systems

This shift also opens up a new theoretical vocabulary for cognition. Concepts such as resonance, entrainment, convection, and phase transitions become more relevant than binary switching and static wiring diagrams. The mind, in this view, is not merely the output of circuits firing in sequence but is the emergent property of an electromechanical and fluidic ensemble—a hybrid between field and structure, rhythm and spike.

Box 2: Ethics & metaphors: clarifying cross-kingdom analogies

"The metaphor of the 'plant brain' is not a category error—but a category opportunity" - Reframing cognition through flow

We acknowledge that terms such as "plant cognition," "electrofluidic signaling," or "vascular computation" may evoke unease due to their apparent anthropomorphic tone. However, this manuscript adheres to a rigorously mechanistic and evolutionary understanding of these phenomena.

Historical Context: The "animal spirits" of Galen, Avicenna, and Descartes were not naïve notions, but precursors to modern understandings of fluid-mediated neural function—rooted in the most advanced physical models of their time. Bose's experimental biology rigorously documented action potentials in Mimosa pudica plant and the coupling of voltage and turgor—arguably a non-neuronal cognitive substrate. Contemporary plant neurobiology (e.g., Baluska Baluška et al. (2004) & Mancuso Baluška and Mancuso (2009)) and fluid dynamics of the glymphatic system (e.g., Nedergaard Nedergaard (2013), Xie Xie et al. (2013), Fultz Fultz et al. (2019)) show that rhythmic entrainment, memory encoding, and adaptive behavior can occur in systems devoid of classical neurons.

Clarification of Intent: This manuscript does not assert that plants "think" in the same sense as humans, nor the glymphatic system performs symbolic logic like a CPU. Rather, it proposes a shared physical substrate—fluidic, oscillatory, electrically modulated—that enables adaptive information handling across life forms. A continuum between fast, digital neural codes and slow, analog flow-based computations. That cognition itself may be an emergent property of flow, not a monopoly of spikes.

Guiding Principle:

"Metaphor becomes mechanism when matched with measurement."

The purpose of this framework is not to anthropomorphize but to re-expand the computational imagination of biology—to allow non-neuronal, non-digital substrates their rightful place in theories of brain, behavior, and life. Fig. 6 shows a comparative diagram linking electro-fluidic features of plant and brain's fluidic systems.

Marginal Callout: Ethics & Epistemology Across Kingdoms:

"Calling a plant intelligent does not mean it thinks like us. It means we are thinking too narrowly."

As plant electrophysiology and brain fluid dynamics converge in language—terms like "plant brain," "vascular computation," "non-neuronal cognition"—it is critical to distinguish metaphor from mechanism: We do not claim that plants possess consciousness or that glymphatic flow encodes binary information. We propose that analog, fluid-based signaling represents an evolutionarily conserved substrate for adaptation, regulation, and information flow, and that "cognition" can be reframed as a material phenomenon—arising from rhythms, geometry, and gradients, not only spikes and synapses Historical Echo: From Descartes' animal spirits and Galen's pneuma to Bose's fluid-electric pulvinus, science has long wrestled with the idea that intelligence might flow before it fires. Let us not ask whether plants have a brain, but whether the brain still carries a memory of the plant.

Ethical Note: On Metaphors, Mechanisms, and Cross-Kingdom Analogies: Throughout this article, we draw deliberate analogies between plant electrophysiology, animal neural systems, and fluidic computational architectures. We acknowledge that terms like "plant brain," "cognition," or "computation" carry species-specific connotations, and may invite concern about anthropomorphism or overextension of metaphor.

It is not our intent to equate plant behavior with human subjective experience, nor to claim that glymphatic circulation performs logic operations in a Turing-equivalent sense. Rather, our proposal is that there exists a shared computational substrate—defined by flow, feedback, and entrainment—that spans across kingdoms and precedes the evolution of specialized neurons. By using terms like electrofluidic computation, we aim to highlight a mechanistic continuum rather than a categorical identity. Much as the term "metabolism" applies across vastly different species, we suggest that computation—broadly defined as the transformation of inputs into structured outputs—can emerge in non-neuronal, non-digital systems via fluidic dynamics. Framing the brain as an electrofluidic system does not diminish its uniqueness; rather, it situates it within the broader architecture of life—where cognition arises not solely from synaptic circuits, but from the deeper choreography of circuits and currents.

11 Conclusion

In this article, we present a historical exploration tracing a broad arc from ancient metaphors of "animal spirits" to the cutting-edge science of extracellular signaling, CSF dynamics, and vascular computation. At each stage, we have seen how fluid-based phenomena—once relegated to metaphor or physiological maintenance—have re-emerged as central to our understanding of cognition. The historical narrative shows that the early thinkers, constrained by the limits of contemporary science, intuited aspects of neural function that modern technologies are only now beginning to confirm and refine. Recent translational approaches propose tracking intrathecally administered contrast agents (e.g.,

gadolinium) via blood and/or urine to non-invasively infer glymphatic clearance. Similar to Bose's tracing of sap ascent via oscillatory responses, such methods offer a modern electrofluidic readout of cerebrospinal circulation.

By integrating historical, experimental, and computational insights, we have argued that the brain does not merely compute with electrical signals across a synaptic mesh. It also operates through a set of deeply embodied, evolutionarily conserved fluidic mechanisms that shape, constrain, and enable brain's computations. These systems—CSF, ECS, blood vessels, and glial scaffolds—are not passive substrates but dynamic processors of information, co-participants in the ongoing activity we call brain function. The implications are profound. If cognition arises not solely from spiking networks but from an interplay of circuits and currents, then our models of the brain must shift from static wiring diagrams to hydrodynamic topologies. Computational neuroscience must begin to account for diffusive, convective, and entrained flows, not just discrete impulses. Artificial intelligence systems inspired by biology might benefit from incorporating such principles of analog, material, and field-based computation.

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